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13. ABSTRACT (Maximum 200 words)

A stand-alone generator that is capable of producing one kWatt was developed during the contract period. Power to weight ratio has been improved from 10 Watts/K to 50 Watts/K. Exhaust emissions are less than 1 PPM HC and 300 PPM CO. NOx emissions are still high but a Rhodium or Rubidium flash coating on the metal recuperator surface should get below the 15 PPM target.

The automated start up and run program works well and allows one switch operation. Water cooling and noise suppression were achieved early in the program and cooling efficiency has been dramatically improved. Efficiency has been improved from marginal net power output to an efficiency of 7%.

System modeling development has allowed pinpointing areas of efficiency loss and allows rapid optimization of cells and optical cavity. Work with matched emitters and improved recuperators have brought about improved combustion efficiency.

Work on Tungsten coated matched emitters have begun although it appears that a hermetically sealed emitter must be used to prevent rapid oxidation of the metal. Shingle cell circuits have been designed, manufactured and tested.

14. SUBJECT TERMS
thermophotovoltaic, TPV, photovoltaic, PV, generator, cogeneration, Western Washington University, WWU, JX Crystals, gallium antimonide, GaSb, silicon carbide, high temperature, recuperator, peak power tracker, emitter, optical filter, spectral control, thermal management

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REPORT DOCUMENTATION PAGE (SF298)
(Continuation Sheet 1)

1. Statement of Problem Studied

The goal for the project was to design and build a multikilowatt thermophotovoltaic (TPV) generator. Although preliminary work indicated that a water cooled TPV generator would certainly produce power it was not certain that a self-contained unit could operate efficiently enough to provide net power above the amount required to pump water and run the air supply and cooling fans. In addition, it was deemed necessary for the unit to operate with exhaust emissions at reduced levels from that of existing generator sets.

Solutions for the problem were thought to be in:

1. Improving cell efficiency by developing a cell optimized for a black body emitter.
2. Establishing even temperature over the entire emitter surface.
3. Developing materials to allow higher temperature operation of the emitter.
4. Reducing heat loss by convection and conduction.
5. Development of filters and selective emitters that allowed only photons capable of exciting the photo cells to reach the surface of the cell and returning out of band energy to the emitter.
6. Developing recuperators capable of returning a high percentage of exhaust heat to the incoming air without incurring too much flow restriction and pumping loss.
7. Measurement and control of exhaust emissions

2. Summary of Most Important Results

1. Liquid phase epitaxy equipment installed and made operational at JX Crystals Inc.

2. Inert gas atmosphere high temperature furnaces acquired and made operational.

3. Instrumentation, packaged, designed and made operational

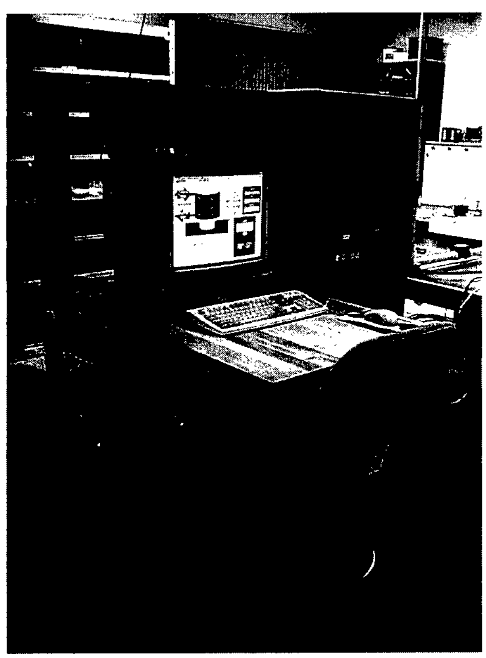

Figure 1 - Computer Controlled Instrumentation

4. CNC milling machines, turning center and wire electric discharge acquired and made operational for manufacture of TPV components.

5. Personnel and senior students trained in use of advanced software for CNC operation of machine tools.

6. 1 Watt/cm^2 achieved on air cooled 84 cell circuit and 2.4 Watts/cm^2 achieved on flash lamp test of 10 cell circuit.

7. Succeeded in operating units on Butane, propane, methane and acetylene.

8. Although early combustion chambers were noisy, we have been successful in suppressing noise on all subsequent burners. Development of three conic diffuser combustion chamber ceramic mixer provides very good start-up performance, high combustion efficiency and silent operation.

9. Measured exhaust emissions from a one kW burner are less than 1 PPM total HC, 300 PPM of CO and 151 PPM NO_x. Although NOx readings were 6 times the goal, a flash plating of Rhodium or Rubidium should reduce NOx emissions to less than 15 PPM.

10. Early in the project we determined that lower photon emission to the end cells in the series array led to marked drop in series circuit efficiency compared with single cell tests. The first solution was to increase the size of the end cells so they wouldn't drag down series cell string efficiency. Later we discovered that through use of a two pass up down combustion system inside the emitter tube that it was possible to run both ends of the emitter about 50 degrees Celsius hotter than the center. We could use the same size cells at all positions and take very small losses in efficiency compared to single cell tests. Careful control of annular spacing of the up and down tubes and the central plug allowed very good control of emitter temperature for the complete length.

11. Use of optimized density internal machined fins the water-cooled cell receivers have provided a marked reduction in cell temperature with no increase in cooling water flow.

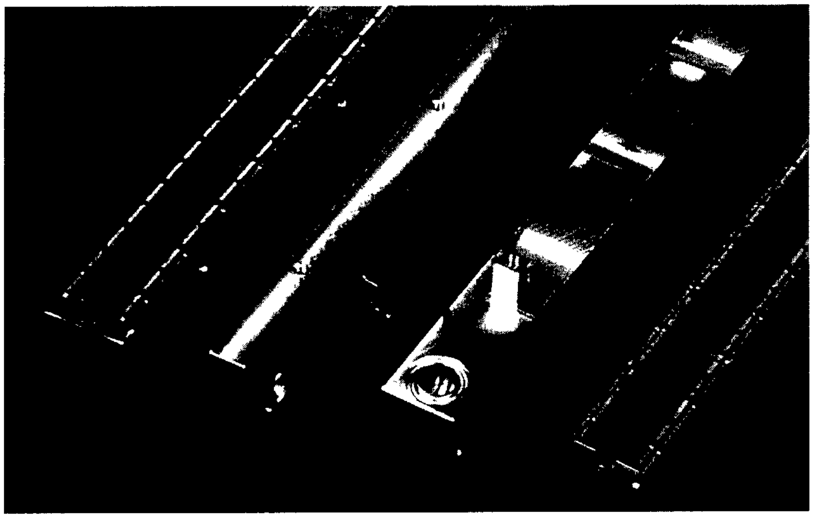

Figure 2 – Cell Receiver

12. We have progressively improved power to weight ratio from 10 Watts/Kg to 50 Watts/Kg. During the contract period, we have designed and constructed arrays with continual reductions in parasitic losses due to gaps between cells and area exposed to radiant energy that cannot create power. Initially it was thought that light could be concentrated through use of appropriately shaped mirrors to increase the photon density on the active cell materials to increase efficiency as had already been demonstrated by the Fraas concentrator sandwich type photocells for satellite use. We soon discovered unlike the collinear light from the sun the non-collinear light from our emitters could not be focussed. The best that we could hope for from mirror is that useable light energy could be returned to the emitter to keep it hot and save additional fuel usage.

13. It soon became apparent that photons outside the wavelength that energize the photocell i.e. (.8 to 1.2 microns) should not be allowed to reach the surface of the cell where they would merely lose their energy through the cooling water behind the cell. Two approaches to this problem were tried.
    a) Filters were designed and built which tend to pass useful wavelengths and reflect back to the emitter unusable photons. Unfortunately this approach so far has not been very successful because the transmissive to reflectance ratio has not been very high and because during the transmission through the quartz connective shields some out of band energies lost to the quartz and re-radiated at still lower energy toward the cells.
    b) A more promising approach was to coat the surface of the emitter with a material that only emits in the desired bandwidth. Tungsten metal has proved to be successful coating for a selective emitter but unfortunately is oxidizes readily at TPV temperatures. We did build a vacuum chamber TPV that system to test for convective losses through the optical cavity. Although test cylinders have been made from silicon carbide with tungsten coatings we have not at this date tested complete vacuum chamber tungsten coated selective emitter systems.

14. System modeling: New and improved numerical models have been developed. The combustion gas to emitter heat transfer model (COMBEMIT) has been substantially refined, with improved modeling accuracy. Further refinement has also been carried out on the radiation cavity performance model (EMTCELL). These refinements include the addition of

the parasitic cavity losses such as cell grids and gaps between cells. Thorough treatment of these models can be found in the paper – "Practical Development and Theoretical Modeling of a Complete TPV Generator" published in TPV3 Conference Proceedings.

15. At the beginning of this contract, there was no facility in the US growing GaSb crystals. We have now grown both 3" diameter and 4" diameter crystals using Czochalski crystal pullers purchased and installed at JX Crystals Inc. in 1996.

16. View factor has been continuously improved during the contract period. By using a larger 3" emitter and holding the cell face diameter at 5.25". The early units had a view factor of only .31 and the latest units have risen to .57. An 84% improvement. The latest version of combustion diffuser is much easier to manufacture, is more durable and is more effective at providing ideal turbulence in combustion.

17. System efficiency has been continuously improved during the contract period. During the last year of the project, system efficiency was sustained while improvements in durability and portability were improved. The system control system was developed to allow one switch startup and running with completely automated control of the experimental unit.

18. Much attention has been paid to reducing system weight. Thinner section aluminum water-cooled receivers and manifolding uses a lower weight of structure and the internal finning of the receiver water galleries allows a small quantity of water in the system

19. The improvement in heat transfer by a factor of five has allowed a smaller water pump that not only weighs less but also provides lower power draw. Extensive use of proE software and the CNC machine tools purchased under this contract has enabled us to dramatically improve power to weight ratios.

20. Large Cell Array Development: As an outcome of the research during 1997, we concluded that improvements in power and efficiency could be achieved by using a large size cell in the array. Before JX Crystals could produce such a cell, an analysis tool had to be developed to analyze potential gridline designs. Western Washington University worked closely with JX Crystals in the development of an analysis tool that determines the effects of grid design changes on cell performance. Specifically, the analysis accounts for gridline geometry and spacing, bus bar geometry, and PV cell diode emitter and base characteristics.

    Once this analysis tool was developed and checked against JX Crystals' current production cells it was used in the development of the new cell design. The cells were first laid out on the new 3" wafers and then the grid geometry was developed. With the die size and grid design fixed, artwork was drawn up at JX Crystals and production of the 0.65" square cells begun.

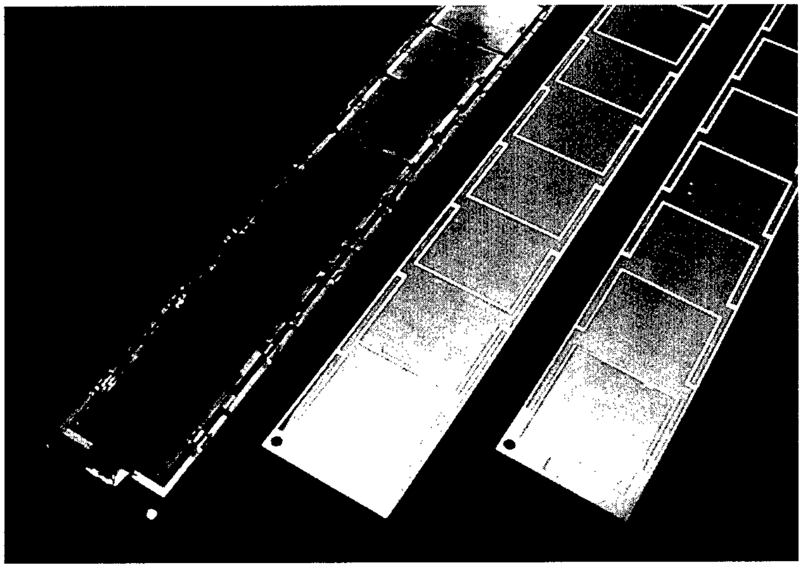

Figure 3 - Three of the New Large Cell Circuit Boards – One Assembled.

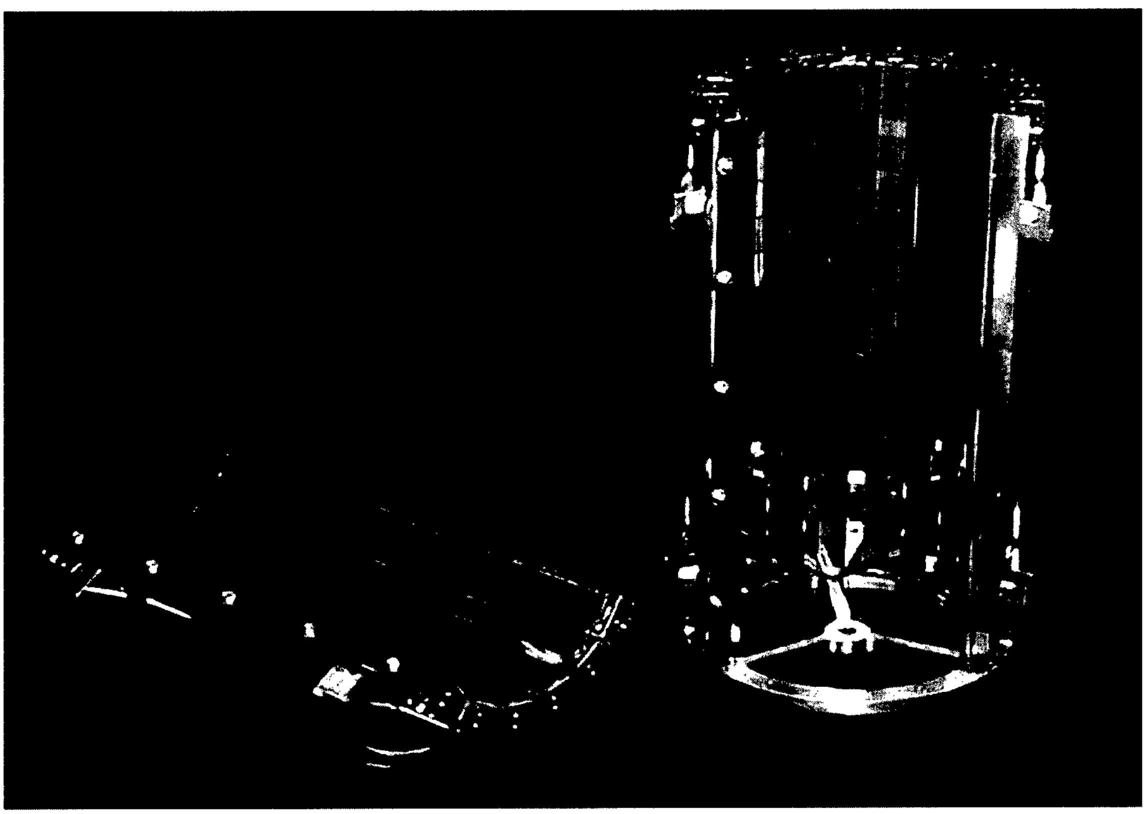

Figure 4 - A Full Compliment of Large Cell Receivers on the Array Assembly Fixtures

New array geometry has been developed based on the new 0.65" square cells from JX Crystals. From data collected using the individually pinned circuit it was determined that larger end cells were unnecessary in the array. The new array design uses 18 strings of 15 cells each that result in an array of similar geometry to the current array but using only one cell size. Based on modeling projections we expected an increase of about 10% in both array power and array efficiency. Problems in cell production and mounting however negated this hoped for improvement.

The new array design has been completed and production of the array components is completed. A new jumper lead has been designed and a lead-forming tool has been manufactured to form these leads. Two full sets of jumper leads have been produced by WWU to be used by JX Crystals in the assembly of the circuits. The circuit boards were etched by Thermagon and post manufactured by WWU. Two cylinders worth of the larger .65" cells have been produced and tested by JX Crystals. Finally, JX Crystals has assembled the two cylinders worth of circuits using the WWU circuit boards, jumper leads and tooling.

In addition to the completion of the 36 circuits required for the two cylinders, the water-cooled receivers have been manufactured. These receivers are functionally similar to the 160 receivers which began were designed and manufactured for the DoE TPV8 generator. The new receivers include the internal fin geometry that has been successful in the previous designs, while incorporating a new water gallery inlet design. This new water gallery inlet allows the water gallery to be relocated to a position surrounding the exterior ends of the receivers. By relocating the water galleries, the heat transfer from the emitter through the end insulators directly to the water has been virtually eliminated. The addition of a new fixturing system and mounting bosses on the receivers allowed for a more efficient assembly of the new receiver array.

27. Shingled Cell Array Development: Through cooperation with JX Crystals, the idea of shingling the cells within the TPV array has gained new significance. Although the idea of shingling PV cells to improve the packing factor is not new, this concept had been put aside due to thermal mismatch concerns between the Gallium Antimonide (GaSb) cells and the substrate. JX Crystals located a metal matrix composite product manufactured of Aluminum and Silicon Carbide (AlSiC). This new material has a coefficient of thermal expansion (CTE) which closely matches the CTE of GaSb.

By manufacturing the substrates for the shingled GaSb cells out of the AlSiC material the thermal stresses in the cell should be held to an acceptable level. By shingling the cells, the gaps between adjacent cells were eliminated and shingling the cells will reduce the inactive border area at the top and bottom of the cells by half. Finally, interconnects at the edges of the cells will be eliminated and the area between the cell strings currently covered by mirrors will not be required. The resulting increase in active cell area within the cavity should allow for higher power levels at a given emitter temperature and the reduction of parasitic losses should increase efficiency.

Unfortunately difficulties with the AlSiC provider caused warping in the substrate which required an increase in gap between the series strings so that short circuits would not occur. Therefore, though manufacturing costs dropped significantly the power and efficiency did not improve as the necessary increase in clearance almost negated the expected view factor

improvement. Further work with enameled cast iron shingle cell substrate looks very promising.

28. Recuperator Improvements: The newly developed metal recuperator has increased the efficiency from 65% to 80% for the low temperature section. To evaluate the new and previous recuperator performance, a testing process has been developed including the required analytical procedures. This testing process determines both the recuperator efficiency and the pressure required to push the gas through the recuperator. See figure 5 for a view of the new recuperator.

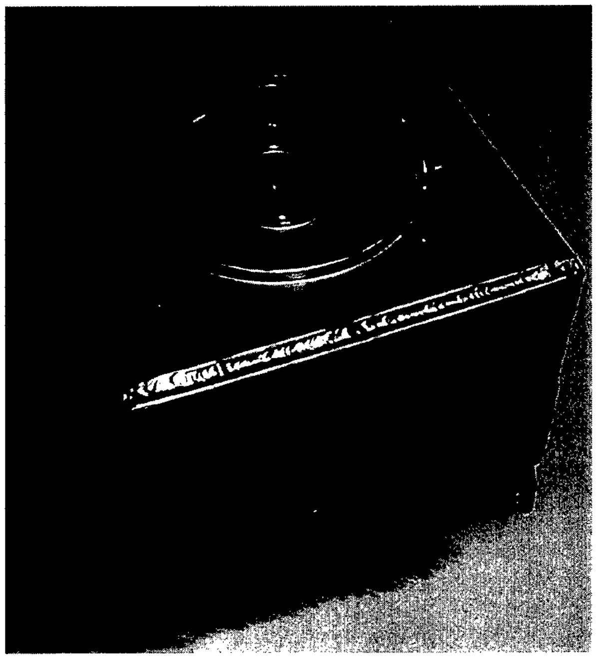

Figure 5 - Square Stainless Steel Recuperator

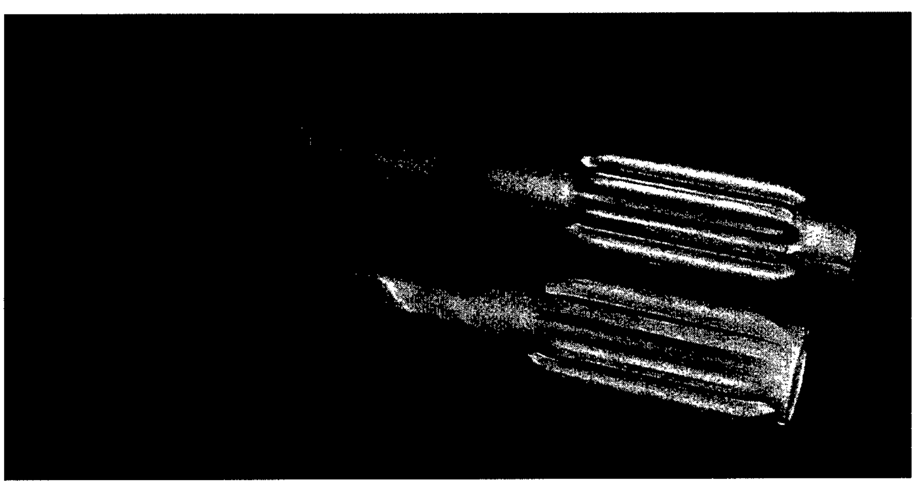

Figure 6 - Silicon carbide Recuperators

To improve the performance of the high temperature ceramic section of the heat exchanger a new convoluted wall recuperator has been developed. First, a ceramic industry partner was selected to accomplish the manufacturing of the new design for the ceramic recuperator. Once manufacturing requirements were fully defined a component geometry was developed using Pro/ENGINEER® modeling software. The solid model was then used within the Pro/NC® manufacturing environment to generate the tooling paths for our CNC milling machine. A complete set of molds were then machined and finished for the molding of the silicon carbide heat exchanger. Finally, these molds were shipped to the ceramic manufacturer, who produced eight prototype units. See figure 6 for a view of the new silicon carbide recuperator.

29. The 15kW cylindrical array characterization unit: A new 15 kW electrically heated receiver test station was developed to evaluate changes made to the radiation cavity system. The 15kW cylindrical array characterization unit receives input power from a separate building circuit installed for this application. This new circuit provides 480V input at 60A. Like the 6 kW test station, this system also uses an SCR to regulate power to the heating element. The heating element is a 3-inch diameter I^2R, Inc. Starbar™ with an 11Ω nominal resistance. An Acme buck transformer drops the voltage to the element from 480V to 436V. A 480V to 115V transformer is used to power the onboard PID control, watt transducer, panel meter, and cooling fan.

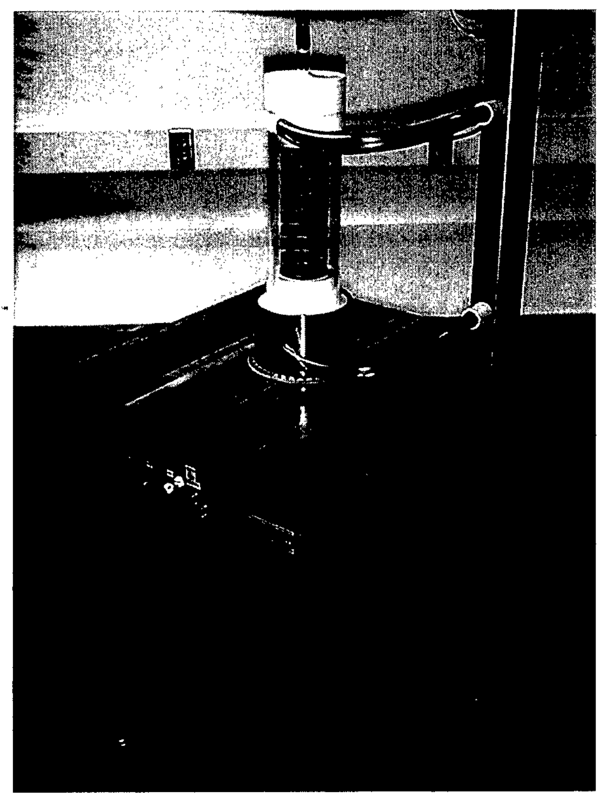

Figure 6 - 15 kWatt Test Station

The Starbar™ is surrounded by Zircar SALI™ alumina fiber insulation at the connection end of the element, which is air-cooled. A current-transformer on the input line to the heating element measures element input current from the SCR. The current-transformer is connected to a watt transducer that measures the voltage drop across the heating element, and outputs the product of these two values to a digital panel meter in the same manner as the 6KW unit. The 15KW system also sends the output signal to a National Instruments™ data-acquisition system (NIDAQ) to enable real time data analysis and data logging. The NIDAQ uses Lab-View™ data analysis software running on a Pentium-II® 300mhz PC for data collection and analysis purposes. The NIDAQ can also be used to control the input power to the heating element for automatic ramp-up to a preset input power level or temperature setting.

30. TPV System and Research Enhancement: To reduce the cell temperature and improve the heat transfer to the cooling system a new higher performance circuit board material has been located and evaluated. This material, manufactured by Thermagon, has a ceramic powder filled epoxy dielectric coating over an aluminum or copper circuit board. Replacing the previous circuit material with the Thermagon circuit board material reduces the temperature drop through the circuit board by 80%. This allows the cells to run cooler given a set heat load and heat rejection temperature.

    To maximize the efficiency of the TPV system a Peak Power Tracker (PPT) is needed to adjust the load on the TPV array to its optimum operating point. To accomplish this a complete definition of performance and hardware requirements for a PPT was carried out for the Army's needs. A suitable PPT and inverter were located and purchased for the generator. In addition, the eight PPT's which were developed for the DoE contract by Xantrex, have all been delivered. We are continuing to use the Xantrex PPT's in the MURI research to provide stable loads for the arrays during bench testing.

    The flash test technology was transferred to WWU and a new flash illumination circuit test apparatus was built and implemented at WWU. This flash tester has been used extensively in an effort to develop the "best in class" TPV receiver array. A process was developed to test and sort the entire inventory of TPV circuits and assemble a performance-matched array. Additionally, testing has been carried out to evaluate the effects on output power as a result of cell temperature. Finally, an apparatus was developed and utilized to investigate the effects of the angle of incidence of the irradiation on the TPV circuits.

31. JX Crystals has developed a number of different approaches to developing matched emitters that will emit only in the .8 micron to 1-2 micron band that the GaSb cells can transmit electrical power. The most successful design seems to be tungsten coating on the now standard SiGb emitter/ceramic recuperator tube. Major difficulty with this technology is that an oxide of tungsten forms quickly at high temperature, which interferes with selective emissivity. Work with a hermetically sealed, possibly back fitted with inert gas seems to by pass this problem and simultaneously reduce conductive and connective losses to very low levels.

32. Shingled Cell Array Development: This array uses eight 2.0" wide circuits with three parallel rows of cells on each circuit. The cells on the circuits are shingled so that the electrical connection from one cell to the next is direct – bottom to top – with no need for external wiring. The circuit substrate is manufactured from the AlSiC material currently used by JX Crystals. The coefficient of expansion of the AlSiC matches the GaSb so that there is a

minimal amount of thermal stress introduced into the fragile cell material. The AlSiC material – which is electrically conductive – has a plasma sprayed coating of alumina to provide an insulating layer. The solder pads for the cells are applied to the alumina using a vapor deposition process with a shadow mask. See Figure 7 for a picture of a completed shingled cell receiver.

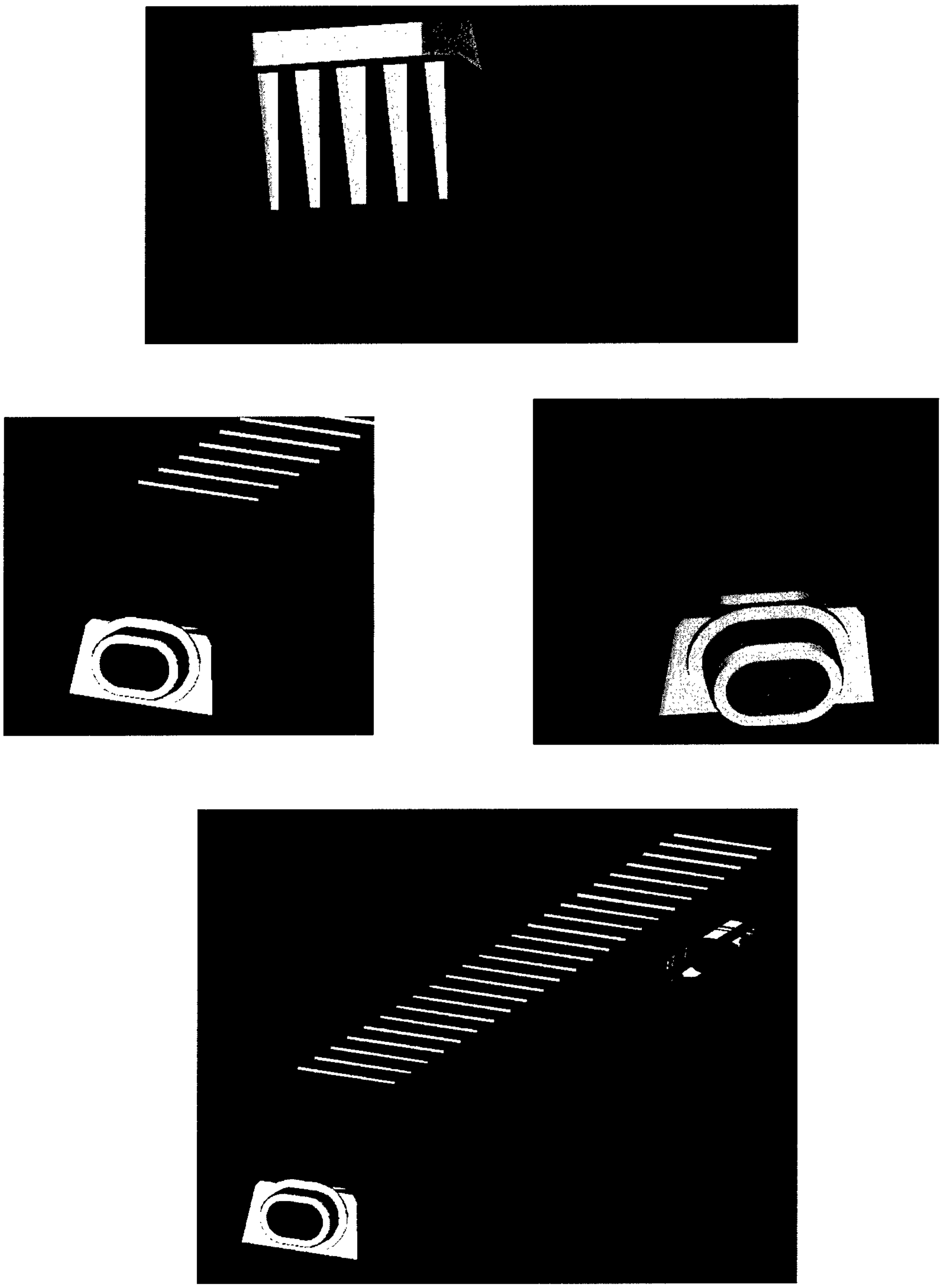

Figure 7 - Shingled Cell Array

The circuit substrates are water cooled by internal fins similar to the current DoD receivers. The fin material is folded up from copper sheet and is then compressed to achieve a higher fin density. The fin material is then soldered to the back of the AlSiC circuit, which has a plasma sprayed layer of babbitt on the back to facilitate the soldering process.

Finally, the completed circuit assemblies are adhesively bonded into a machined aluminum receiver housing. This housing provides the water cooling passage and water fittings as well as the mechanical mounting points to assemble the receivers into the water galleries. See Figure 8 for a view of the completed shingled cell cylinder.

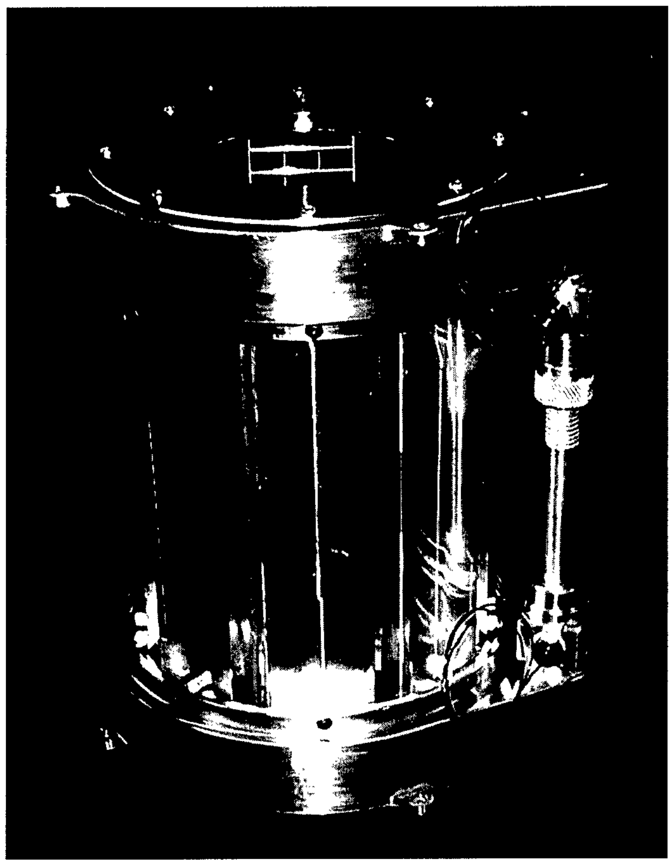

Figure 8 - Complete Shingled Cell Cylinder

To enhance the overall TPV generator system, a reduction of ancillary loads and the automatic operation of the TPV generator system have been achieved.
Ancillary component improvements include the development of a 24V variable speed high-efficiency water pump to circulate the cooling water and a 24V high-efficiency cooling fan with pulse width modulated variable-speed controller to circulate the cooling air. Each of these new ancillary components consumes about one-third less power than previous components. In addition, the speed of the pump and fan are automatically controlled to further improve their efficiency.

The automation system includes a variety of important enhancements to all of the previous generator systems. It now includes a completely automated start-up cycle that purges the burner, sets the blower flow level, turns on the hot-surface igniter and introduces the correct

amount of fuel. The fuel flow rate is controlled via a current driver circuit that powers a proportional flow valve. When the burner is lit, the igniter is turned off and the automatic air-fuel mixture control adjusts the air and fuel flow rates to optimize combustion. The air flow and air-fuel ratio is controlled through the PID control software that is integrated into the data acquisition and control system. Once through the start-up sequence, the control system ramps the burner up to full operating load and maintains the system at peak efficiency until the power is no longer needed. The system is then shutdown automatically, cooled and will be ready for the next power demand.

Stand Alone TPV Generator Development: An all-new stand-alone TPV generator has been developed. This generator system includes: a combustion and cooling fan, a burner with recuperator, an array, a peak power tracker, an inverter for 120-volt AC power, a starting and load leveling battery, a self-contained cooling system, and an automatic control system. See Figure 8 for a picture of the stand-alone TPV generator. This generator incorporates all of the component enhancements discussed in this section of the paper. This TPV system represents the most highly developed TPV research prototype in existence.

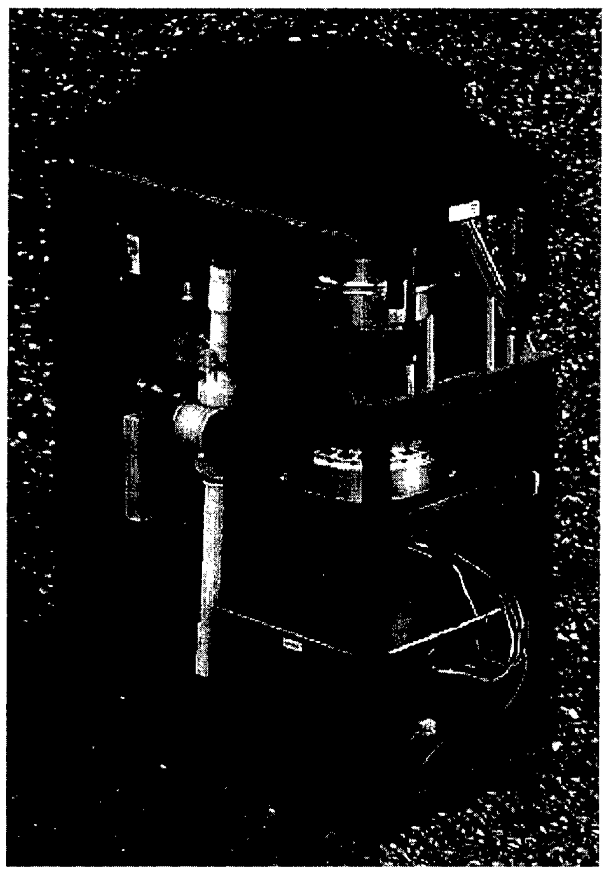

Figure 9 - 1 kW Generator Demonstration Unit

3. Areas for Future Development:

1. Improvement in Cell Efficiency
   - Larger cell size with passivated edges and submerged grid in laser grooves at top of cell.
   - Sandwich cells
   - Vacuum enclusure of cell and emitter

2. Development of selective emitters – eg tungsten coated SiC in non oxygen environment.

3. Integration of ceramic recuperator with emitter.

4. Inside out or flat plate configuration might be better for energy concentation.

4. LIST OF MANUSCRIPTS PUBLISHED

Technical Papers:

- Fraas, L. M., Ferguson, L., McCoy, L. G., Pernisz, U. C., *SiC IR Emitter Design for Thermophotovoltaic Generators*, Second National Renewable Energy Laboratory Conference on Thermophotovoltaic Generation of Electricity, Colorado Springs, CO, July 1995.

- Fraas, L. M., Ziang, H.H., Samaras, J., Ballantyne, R., Williams, D., Hui, S., Ferguson, L., West, E. *Development of a Small Air-Cooled "Midnight Sun" Thermophotovoltaic Electric Generator*, Second National Renewable Energy Laboratory Conference on Thermophotovoltaic Generation of Electricity, Colorado Springs, CO, July 1995.

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- Christ, S., Seal, M. R., Campbell, G., Fraas, L. M., *Viking 29 - A Thermophotovoltaic Hybrid Vehicle Designed and Built at Western Washington University's Vehicle Research Institute*, SAE Future Transportation Conference, Aug. 1997.

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- Fraas, L., Samaras, J., Mulligan, W., Avery, J. Groeneveld, M., Huang, H., Hui, S., Ye, Shi, West, E., Seal, M., *Status of TPV Commercial System Development Using GaSb Infrared Sensitive Cells*, July 1998.

- West, E., Seal, M., Connelly, W., Morrison, O., *Integrated Development and Testing of Multi-Kilowatt TPV Generator Systems*, 4th NREL Thermophotovoltaic Generation of Electricity Conference, October 1998, Colorado.

- Morrison, O., Seal, M., West, E., Connelly, W., *Use of a Thermophotovoltaic Generator in a Hybrid Electric Vehicle*, 4th NREL Thermophotovoltaic Generation of Electricity Conference, October 1998, Colorado.

- Connelly, W., West, E., *Cylindrical TPV Array Characterization*, 4th NREL thermophotovoltaic Generation of Electricity Conference, October 1998, Colorado.

- Fraas, L., Avery, J., Ye, S., Gregory, S., Ballantyne, R., Lamson, D., Schafer, J., *Heat Your Family Room with a Midnight Sun Gas Fired TPV Stove, The Romance and Electricity are Free,* 4th NREL Thermophotovoltaic Generation of Electricity Conference, October 1998, Colorado.

- Fraas, L., Samaras, J., Mulligan, W., Huang, H., Seal, M., West, E., *Development Status on a TPV Cylinder for Combined Heat and Electric Power for the Home*, 4th NREL Thermophotovoltaic Generation of Electricity Conference, October 1998, Colorado.

- Fraas, L., Groeneveld, M., Magendanz, G., Hui, S., Custard, P., *A Single TPV Cell Power Density and Efficiency Measurement Technique,* 4th NREL Thermophotovoltaic Generation of Electricity Conference, October 1998, Colorado.

- Fraas, L., Avery, J., Ballantyne, R., Daniels, W., *"GaSb Photovoltaic Cells Ready for Space and the Home",* IIV Review, vol., 12 mo. 4. 1999

5. Thermophotovoltaic Vehicle Displays

- Viking 29 was displayed from New York to Washington D.C. as part of the American Tour de Sol sponsored by NESEA in May 8-15, 1998.
- Viking 29 was displayed at the 4th NREL Thermophotovoltaic Generation of Electricity Conference, October 11-14, 1998, Colorado.

6. Media Coverage

- Coutts, T., Fitzgerald, M., "Thermophotovoltaics," in *Scientific American*, September 1998, pp. 90-95
- Coutts, T., Fitzgerald, M., "Thermophotovoltaics: the potential for power," in *Physics World*, August 1998, pp. 49-52
- BBC1, England, 10 minutes program on Viking 29 – TPV car.

7. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING

Dr. Michael Seal
Edward West
William Connelly
Orion Morrison
Mikhail Shkurat
She Hui - Visiting scholar from China at JX Crystals
Mitch Groeneveld – M. Sc. University of Washington
Lucus Ferguson – M.Sc. University of Washington
Edmund Rauser – graduated 1997, B.Sc., Western Washington University
Miles Elledge – Graduated June 1998 with B.Sc. from Western Washington University
Cameron Miller – Undergraduate working toward B.Sc. from Western Washington University
James Rau – Undergraduate working toward B.Sc. from Western Washington University
Ralph McBride - Undergraduate working toward B.Sc. from Western Washington University
Gregory Montgomery - Undergraduate working toward B.Sc. from Western Washington University
William Ueda - Undergraduate working toward B.Sc. from Western Washington University

8. REPORT OF INVENTIONS

- US Patent 5,512,109: Generator with Thermophotovoltaic Cells and Hydrocarbon Burner: with Edward West and Michael Seal, assigned to JX Crystals.
- US Patent 5,551,992:Thermophotovoltaic Generator with Low Bandgap Cells and Hydrocarbon Burner: with Edward West and Michael Seal, assigned to JX Crystals.

- JX Crystals applied for the following patents, listed below:
  - Coarse Grain Polycrystalline Gallium Antimonide TPV Cell
  - Antireflection Coated Refractory Metal Matched Emitters for use in TPV Generators.
  - Linear Circuit Designs for Solar Photovoltaic Concentrator and TPV Applications Using Cell and Substrate Materials with Matched Coefficients of Thermal Expansion.
  - Shingled circuit technology

9. Educational Enhancement

The ability of the Engineering Technology Department to provide students with curriculum utilizing state of the art engineering software and manufacturing tools continues to be enhanced through the MURI contract.

- Pro/ENGINEER® solid modeling software has been integrated into the curriculum.
- New $200,000 computer lab donated by Boeing Company as a result of the ProE solid modeling software already in place through MURI grant is operational and is in use 45 hours a week.
- The Engineering Technology Department has extended the MURI investment through the hiring of an instructor to teach the ProE classes.
- Enhanced CNC machining capabilities have allowed the department to expand the number of students per section.
- Student design teams are utilizing MURI funded CNC equipment to manufacture components.
- TPV as a method to generate power has been integrated into the advanced power course.
- The beginning steps have been taken by the university administration to get legislative funding for a hot metals annex. This will allow the appropriate equipment purchased under MURI to be integrated into the manufacturing curriculum.

10. Facilities Enhancement

Over the past year, effort has continued to improve the working conditions and organization of the research lab area. The test area has been reorganized with the modification of the test bench to streamline the testing process. Further equipment acquisitions are as follows:

- A Lagun three axis manual mill with a 4-hp spindle for prototype component production.
- A Clausing 15" lathe with angle attachment and Digital Readout for precision manual turning.
- A four axis wire EDM for components that cannot be produced by conventional techniques.
- A high-end PC for use with Pro/ENGINEER and Pro/NC computer aided manufacturing software.
- A wide selection of precision measuring tool used for quality assurance of prototype components.
- A new Kurz flow meter for the fuel flow measurement going to the TPV burner.
- Designed and constructed new high output 3" array test station.
- Power has been installed in lab area for new test station (480VAC 3phase).
- A PC installed at WWU for the circuit flash testing system built by JXC.
- High power flash bulb, power supplies and data acquisition board for flash tester.
- New tooling cabinets and bench tops for streamlining and securing the CNC production area.

11. TECHNOLOGY TRANSFER

- McDermott Technologies and JX Crystals are developing a 500-watt TPV generator, for a DARPA contract, which utilizes a receiver array designed and manufactured at WWU.

- JX Crystals has developed a 2.75" diameter high-powered receiver test station using technology developed at Western Washington University.

- WWU has transferred the receiver array assembly procedure and technology to JX Crystals.

- JX Crystals is using the new shingled cell circuits in their Midnight Sun stove, which were partially funded under the MURI contract,

- JXC transferred flash illumination technology to WWU and a new flash test apparatus was constructed.

- Xantrex Technologies of Burnaby, B.C. is developing peak power trackers for TPV applications.